Horizontal but not vertical saccades enhance memory retrieval: a meta-analysis and systematic review

Xiao-jing Qin[1,2], Han-xue Yang [1,2] , Ji-fang Cui[3], Jun-yan Ye[1,2], Ya Wang[1,2]*

[1] Neuropsychology and Applied Cognitive Neuroscience Laboratory, Key Laboratory of Mental Health, Institute of Psychology, Chinese Academy of Sciences, Beijing, China

[2] Department of Psychology, University of Chinese Academy of Sciences, Beijing, China

[3] Institute of Educational Information and Statistics, National Institute of Education Sciences, Beijing, China

*Correspondence should be addressed to Ya Wang, Institute of Psychology, Chinese Academy of Science, 16 Lincui Road, Chaoyang District, Beijing 100101, China. Tel: (8610)64881148, Email: wangyazsu@gmail.com, wangya@psych.ac.cn.

Abstract

BACKGROUND: Saccade-induced retrieval enhancement (SIRE) refers to the phenomenon that active engaging of horizontal eye movements before recall would enhance subsequent memory performance. This effect is generally thought to be the result of interhemispheric interaction stimulated by saccades. Nonetheless, recent findings do not fully support this hypothesis. An alternative explanation is that saccades promote memory retrieval by improving top-down attention control. Thus, the mechanisms of SIRE are unclear, the present meta-analysis quantitatively analyzed the effect of saccades on memory performance and examined the mechanisms of SIRE through moderator analysis.

METHODS: We searched "Web of Science", "PubMed", and "Springer" for peer reviewed papers using the keywords "eye movements + memory" and "saccades + memory". Twenty-two papers were included in the final analysis.

RESULTS: There was a significant facilitation of horizontal saccades on overall memory performance, with a pooled effect size (Cohen's *d*) of 0.45 ($p < 0.001$). However, the overall effect of vertical saccades was not significant ($d = 0.1$, $p = 0.14$). Moderation analysis showed that the handedness of participants was a significant moderator of the SIRE, with strongly right-handed individuals benefited more from horizontal saccades than non-strongly right-handed individuals ($p < 0.01$).

CONCLUSION: Horizontal saccades improved memory performances, particularly for the strongly right-handed individuals, these results support the interhemispheric interaction hypothesis.

Keywords: memory, saccades, meta-analysis, interhemispheric interaction

1. Introduction

Saccade-induced retrieval enhancement (SIRE) refers to the phenomenon that active engaging of horizontal eye movements before recall would enhance subsequent memory performance (Lyle & Martin, 2010). Christman, Garvey, Propper, and Phaneuf (2003) firstly described SIRE, in that study, participants were asked to learn a word list first, then guided to visually follow a black dot on the screen which moved horizontally for 30 seconds before recalling the word list. Their results showed a higher sensitivity (d' in signal detection theory) following horizontal saccades relative to no eye movements. Since then, SIRE has been examined in many studies, most of these studies found that horizontal saccades promoted recognition (Christman, Garvey, Propper, & Phaneuf, 2003, Experiment 1;Parker, Relph, & Dagnall, 2008; Lyle, Logan, & Roediger, 2008), free recall (Lyle & Edlin, 2015; Lyle, Logan, & Roediger, 2008; Nieuwenhuis et al., 2013; Parker, Relph, & Dagnall, 2008; Samara, Elzinga, Slaghuter, Nieuwenhuis, 2011), reduced false memories (Christman, Propper, & Dion, 2004; Parker & Dagnall, 2012), and facilitated autobiographical memory (Christman, Garvey, Propper, & Phaneuf, 2003, Experiment 2; Christman, Propper, & Brown, 2006; Parker & Dagnall, 2010; Parker, Parkin, & Dagnall, 2013).

Nonetheless, SIRE has been challenged by some other empirical evidence. For example, a pre-registered collaborative study failed to replicate the enhancing effect of horizontal saccades on memory retrieval and reported contradictory results, i.e., compared with the no eye movement condition, participants' free recall performance after induced eye movements was even worse (Matzke et al., 2015). In addition, whether horizontal saccades are necessary in SIRE remained unclear. Vertical saccades which were often used as the control condition

were also found to enhance words recognition (compared with no eye movement condition, *d* = 0.68) (Lyle et al., 2008; also see Parker et al., 2008). Furthermore, handedness has also been suggested to be an important factor that would affect SIRE. According to the interhemispheric interaction hypothesis, strongly right-handed people have lower baseline level of interhemispheric interaction and they should benefit more on memory performance from horizontal saccades (Christman, Garvey, Propper, & Phaneuf, 2003), though some research findings did not fully support this view (Lyle & Jacobs, 2010). Generally speaking, there are inconsistencies in the research results of SIRE, thus it is necessary to conduct a quantitative review of the existing evidence in order to clarify whether the SIRE exists and examine the potential mechanisms.

According to the interhemispheric interaction hypothesis proposed by Christman, Garvey, Propper, and Phaneuf (2003), horizontal saccades improve memory retrieval by enhancing the interhemispheric interaction of the brain, which is crucial for the retrieval of episodic memory. Two methods were used in previous studies to distinguish the level of interhemispheric interaction. One is to select mixed handed individuals by handedness tests. Since mixed handed individuals have larger corpus callosum (Luders et al., 2010), their level of interhemispheric interaction should be higher than that of right- or left-handed individuals, and consequently, they have better memory performance. The other method is to provide certain visual stimuli to guide horizontal saccades, the level of interhemispheric interaction can be temporarily improved and subsequent memory retrieval enhanced. It is debatable whether the above two methods can separate individuals with different levels of interhemispheric interaction. However, previous studies have shown that memory was

superior in mixed handed individuals than in strongly right-handed individuals (Christman et al., 2006; Christman et al., 2004; Propper, Christman, & Phaneuf, 2005). Moreover, the memory performance of strongly right-handed individuals could be temporarily improved following horizontal saccades. On the contrary, horizontal saccades failed to improve memory performance for non-strongly right-handed individuals, and in some cases even detrimental for their memory performance (Lyle, Logan, & Roediger, 2008). These results provided some support for the interhemispheric interaction hypothesis.

The interhemispheric interaction hypothesis was based on the hemispheric encoding/retrieval asymmetry (HERA) model. This model suggested that the encoding and retrieval of episodic memory involved asymmetrical brain areas. Specifically, encoding is associated with increased activity in the left prefrontal lobe, while retrieval is associated with increased activity in the right prefrontal lobe (Tulving, Kapur, Craik, Moscovitch, & Houle, 1994). Cabeza and Nyberg (2000) summarized PET/fMRI findings and found that the encoding of episodic memory involved the left hemisphere, and the retrieval of episodic memory involved bilateral hemisphere or tended to be right-lateralized. Studies on split-brain individuals also showed that cutting off the connections between the two hemispheres hindered episodic memory recognition (Cronin Golomb, Gabrieli, & Keane, 1996). Based on these evidences, Christman and colleagues (2003) suggested that the interaction between the two hemispheres provides a basis for accurate episodic memory.

To test the interhemispheric interaction hypothesis, several studies have examined the influence of eye movements on Electroencephalogram (EEG) coherence. Propper and colleagues (2007) compared EEG coherence between left and right frontal lobes between eye

movement and control conditions. However, they did not observe any increased interhemispheric EEG coherence following manipulation of horizontal saccades. In Samara's (2011) study, they used a within-group design and compared the changes of EEG coherence before and after saccades. Results showed that although the recognition of emotional words was better following horizontal saccades relative to no eye movements, they failed to observe increased EEG coherence between the two hemispheres following horizontal saccades, and the memory enhancement was not correlated to changes of EEG coherence. In a most recent study, the effects of eye movements manipulation on EEG power and coherence were examined (Fleck et al., 2018). Similarly, this study failed to observe a change in interhemispheric EEG coherence for any of the frequency bands examined.

Taken together, although many studies have demonstrated the enhancing effect of saccades on memory retrieval, there is no direct evidence indicating that this effect was contributed by interhemispheric interaction. Lyle and Edlin (2015) have proposed that saccades may improve memory retrieval by promoting top-down attention control. From this perspective, SIRE can be regarded as the effect of a short attention control “exercise”. If the subsequent memory test primarily relied on top-down attention control, the effect of this eye movement “exercise” would be manifested. On the contrary, if the memory test is simple and depends more on bottom-up spontaneous processing, eye movements would not benefit the performance (Lyle & Edlin, 2015). This theory explains why eye movements manipulation can also enhance performance on other cognitive tests such as attention (Edlin & Lyle, 2013) and creativity (Shobe, Ross, & Fleck, 2009). The “top-down attention control hypothesis” was derived from early neuroimaging studies, which suggested that saccades were associated with

activations of the frontal eye field, intraparietal sulcus, and superior parietal lobe, namely brain regions that have long been implicated in top-down attention control (Corbetta & Shulman, 2002). However, no studies have established a direct relationship between the manipulation of horizontal saccades and activations of attention-related brain regions which lead to enhancement of memory performance.

Discrepancies between the two theories are: 1) According to the interhemispheric interaction hypothesis, eye movements specifically improve memory performance, particularly memory retrieval; the effect is mainly manifested in strongly right-handed individuals who had a lower level of interhemispheric interaction. Only horizontal saccades are effective, whereas vertical saccades do not affect interhemispheric interaction, therefore not beneficial to memory retrieval (Christman, Garvey, Propper, & Phaneuf, 2003); 2) From the perspective of top-down attention control theory, the effect of eye movements is not specific to memory, but to all cognitive activities related to top-down attention control (Lyle & Edlin, 2015). The direction of eye movements will not affect its enhancing effect.

Despite accumulating studies, the mechanisms of SIRE are still unclear. The present study aimed to clarify the following questions through meta-analyses: 1) whether horizontal saccades can enhance memory performance; 2) whether handedness moderate this effect; 3) whether vertical saccades can enhance memory performance. These analyses would help us to understand the underlying mechanisms of SIRE.

2. Method

2.1 Literature search

Databases “Web of Science”, “PubMed” and “Springer” were searched using the combination of keywords "eye movements + memory" or "saccades + memory” for articles published from January 2001 (when Christman & Propper (2001) conducted the first study to examine the relationship between memory performance and interhemispheric interaction) to April 1, 2018. The paper selection process is illustrated in ***Fig.1*** The included studies need to meet the following criteria: 1) published peer-review studies; 2) in which eye movements were manipulated and the differences of memory performance between eye movements and control conditions were compared; 3) used standardized procedures to manipulate the saccades, for example, participants watched a dot that alternately appeared on the left and right side of the screen every 0.5 second; 4) reported sufficient data to calculate the effect sizes. For studies fulfilling other criteria but did not report enough data to calculate the effect sizes, authors of the paper were contacted for potential provision of additional data.

Studies investigating the effect of eye movement desensitization and reprocessing (EMDR; Shapiro, 1989) on the emotionality and vividness of traumatic memory were excluded. Four other studies met the inclusion criteria for eye movements manipulation, but were excluded because they focused mainly on the promotion effect of eye movements on attention (Edlin & Lyle, 2013), creativity (Shobe et al., 2009), or only on EEG signal changes after saccades, without relevant behavioral data (Fleck et al., 2018; Propper et al., 2007).

2.2 Data extraction and study characteristics

Our final analysis included 22 articles, with 28 pairs of data in total, of which 16 focused on episodic memory, 6 focused on false memory and 5 on autobiographical memory and 1 on

face memory (see ***Table 1***). The following information was extracted for each study: 1) the first author and year of publication; 2) the type of experimental design, the number of participants in each experimental group; 3) the materials (sentences, figures, or words) used in the memory test; 4) the direction of eye movements manipulation (horizontal or vertical); 5) whether handedness was measured; 6) the type of memory and main indicators of memory performance. We classified the memory tasks adopted in these studies into four categories: A) episodic memory tasks that included recognition or free recall of words or pictures, B) false memory tasks that induced false recall or false recognition, C) autobiographical memory tasks in which self-related events in daily life were recalled, and D) for those tasks that do not belong to either of the above categories were classified as "Not clear to be classified".[1]

The current meta-analysis distinguished these four types of memory tasks when calculating the effect sizes. We selected the indexes for each type of memory in the following way: First, the main indexes of episodic memory tasks were accuracy, discriminating index d', and the number of correct recollections, our analysis took discriminating index d' as the main indicator. For studies that did not report d', accuracy or the number of correct recollections were regarded as alternatives. Second, the main indicator of false memory is the discrimination index d' of lure words, if d' was not reported, the number of false alarms for key lure words was used. Finally, the indicators of autobiographical memory were relatively

[1] We divided the SIRE studies into categories of episodic memory, false memory, and autobiographical memory. It should be acknowledged that false memory and autobiographical memory cannot be completely separated from episodic memory. These types of memory had different experimental paradigms and different indices of memory performance, thus we explored whether it was a source of heterogeneity of the studies (in our meta-analysis, Q=113.96, p < 0.001). There are mainly three types of tasks in the SIRE studies, one requires participants to learn a word list or pictures, and then participants were given a test for recognition or free recall, one deliberately induces participants to produce false memories, another task requires participants to recall self-related memories without learning any material. Of these three types of tasks, the first one is more in line with episodic memory, the second one is more in line with false memory, and the third one is more appropriate to be classified as autobiographical memory.

subjective, including the numbers of events recalled and the vividness of the recalled events etc. The unweighted average effect size of the main indexes of autobiographical memory were used as the indicator of the effect of eye movements on autobiographical memory.

2.3 Meta-analyses

The Comprehensive Meta-Analysis (CMA, version2.0) (http://www.meta-analysis.com/index.php) was used for data analysis in the current study. We used means, standard deviations and sample sizes to calculate effect sizes (Cohen's *d*). For studies that did not report means or standard deviations, effect sizes were calculated using *t* or *F* statistics and sample sizes. Heterogeneity was assessed by *Q*-statistics, while publication bias was measured by combining funnel plot and Egger's intercept. Duval and Tweedie's trim and fill procedure (Duval & Tweedie, 2000) was also adopted to obtain the adjusted effect sizes. Due to significant heterogeneity of studies included in our analyses, random effect models were used (Hedges & Vevea, 1998).

We first evaluated the pooled effect size of horizontal saccades' effect on memory retrieval. Then we conducted the following moderator analyses: 1) The type of memory. The effect of eye movements on different types of memory performance was compared (in this analysis we only included episodic memory, false memory, and autobiographical memory). 2) Handedness. According to the interhemispheric interaction hypothesis, strongly right-hand individuals are more likely to benefit from horizontal saccades, thus we included handedness as a potential moderating variable. Studies did not report the effect of handedness or distinguish strongly right-handed from non-strongly right-handed individuals were classified

as handedness unknown. 3) In order to understand whether the SIRE effect was selectively caused by horizontal saccades, several studies also examined whether vertical saccades had beneficial effect on memory performance, we also calculated the pooled effect size of vertical saccades on memory retrieval. Finally, publication bias was analyzed. The data for meta-analysis are available upon request.

3. Results

3.1 Effect of horizontal saccades on memory retrieval

3.1.1 Overall effect and subgroup analysis on different types of memory

There was a significant overall effect of horizontal saccades on memory retrieval (Cohen's d = 0.45; 95%*CI* = [0.29-0.62], Z = 5.40, p < 0.001). The heterogeneity of the studies was significant (Q = 113.96, p < 0.001, see ***Table 2***), indicating nonnegligible differences among studies.

Analysis on different types of memory showed that horizontal saccades had a medium to large effect on autobiographical memory (d = 0.68; 95%*CI* = [0.31-1.06], Z = 3.57, p < 0.001), in reducing false memory (d = 0.57; 95%*CI* = [0.23-0.72], Z = 3.28, p< 0.01), and a small to medium effect on episodic memory (d = 0. 0.37; 95%*CI* = [0.14-0.59], Z = 3.22, p < 0.001). There was no significant difference among the three memory categories (Q = 2.37, p = 0.31).[2]

3.1.2 The moderator effect of handedness

Fourteen contrasts in strongly right-handed individuals showed a near medium effect size

[2]Studies on false memory and episodic memory included different types of test. We conducted another subgroup analysis on the type of test. Nine contrasts with free recall test showed a non-significant effect (d = 0.26; 95% *CI* = [-0.01-0.54], Z = 1.86, p = 0.06), 9 contrasts with recognition test showed a medium effect (d = 0.61; 95% *CI* = [0.30-0.92], Z = 3.79, p < 0.001), 4 contrasts with other test showed a small effect (d = 0.17;95% *CI* = [0.02-0.31], Z = 2.29, p = 0.02).

d = 0.45 (95%*CI* = [0.22-0.68], *Z* = 3.81, *p* < 0.001) and significant heterogeneity (*Q* = 36.35, *p* < 0.01); 11 contrasts in non-strongly right-handed individuals showed non-significant effect *d* =-0.06 (95%*CI* = [-0.20-0.09], *Z* = -0.77, *p* = 0.44), the heterogeneity was not significant either (*Q* = 10.12, *p* = 0.43); the 14 contrasts in unknown handedness individuals showed a medium to large effect size *d* = 0.60 (95%*CI* = [0.36-0.85], *Z* = 4.76, *p* < 0.001; see ***Table 3***), the heterogeneity was also significant (*Q* = 52.41, *p* < 0.001). The moderator effect of handedness was significant (*Q* = 34.71, *p* < 0.001). Further pairwise comparisons revealed that memory performance of strongly right-handed individuals benefited more from horizontal saccades compared to non-strongly right-handed individuals (*Q* = 23.82, *p* < 0.001).[3]

3.2 Effects of vertical saccades on memory retrieval

The overall effect size was calculated based on 12 pairs of data comparing vertical saccades with no eye movement condition. The overall effect of vertical saccades was not significant (*d* = 0.10; 95%*CI* = [-0.03-0.23], *Z* = 1.47, *p* = 0.14), with insignificant heterogeneity (*Q* = 7.33, *p* = 0.77). It suggested that memory performance was only benefited from horizontal saccades.

[3] According to Lyle, Hanaver-Torrez, Hacklander, and Edlin (2012), what matters for SIRE is not the direction of handedness (left or right) but whether individuals are consistent-handers. Consistent handers (including strongly-right-handed and strongly left-handed) may show a larger SIRE than inconsistent handers (neither strongly right-handed nor strongly left-handed). Several studies divided subjects into consistent handed group and inconsistent handed group based on the absolute value of handedness test (e.g., Lyle, 2018; Lyle & Edlin, 2015; Lyle et al., 2012; Phaf, 2017). We, therefore, conducted another subgroup analysis on the consistency of handedness. Five contrasts with consistent handed individuals showed a small effect *d* = 0.18 (95% *CI* = [0.01-0.34], *Z* = 2.13, *p* = 0.03), 5 contrasts with inconsistent handed individuals showed the opposite but non-significant effect *d* = -0.17 (95% *CI* = [-0.38-0.04], *Z* =-1.56, *p* = 0.12).

3.3 Publication bias analyses

For the overall effect, funnel plots showed asymmetrical graphics, and the results of Egger's linear regression analysis further suggested notable publication bias (intercept 2.04, 95%*CI* = [0.04-4.04], p = 0.02). After adjusting for missing studies (N = 8, see ***Fig.2***) using the Duval and Tweedie's trim and fill procedure (Duval & Tweedie, 2000), the overall effect size decreased from 0.38 to 0.20 but still significant (95% *CI* = [0.03-0.36]). For the strongly right-handed group, 5 missing studies were added, the effect size reduced from 0.45 to 0.26 but still significant (95%*CI* = [0.03-0.50]). Similarly, after adjustment (N = 5), the effect of unknown handedness individuals decreased from 0.60 to 0.31 (95%*CI* = [0.03-0.6]) but still significant. Detailed results are shown in ***Table 4***. Generally speaking, despite publication bias and the reduced effect sizes after adjustment, our results demonstrated that strongly right-handed individuals could be benefited from horizontal eye movements manipulation, while non-strongly right-handed individuals were insensitive to this procedure. The overall effect was relatively small (d = 0.20) maybe due to the inclusion of non-strongly right-handed participants, but the effect remained robust.

4. Discussion

The current study synthetically and quantitatively analyzed previous studies on the effect of saccades on memory performances, the main findings were: 1) horizontal saccades could improve memory performance, irrespective of memory type; 2) strongly right-handed individuals benefited from the implementation of horizontal saccades while non-strongly right-handed individuals did not benefit from this manipulation; 3) vertical saccades showed

negligible memory enhancement, indicating that episodic memory retrieval was selectively enhanced by horizontal saccades. The results were influenced by publication bias to some extent, however, the conclusions did not change after elimination of publication bias.

The current study yielded a median effect (d = 0.45) of horizontal saccades on memory retrieval, though with considerable heterogeneity (Q = 113.96, p < 0.001). Moderator analysis revealed that handedness was an important source of difference. Effect sizes of SIRE was d = 0.45 for the strongly right-handed group but d = -0.06 for the non-strongly right-handed group, the latter indicated a null effect. Together with previous evidence, we propose three potential reasons for the inconsistencies in this research field: 1) some studies failed to take handedness into consideration, our results suggested it is a moderating factor of SIRE; 2) there was a large variability of the paradigms and memory types among different empirical studies, though the moderating effect of type of memory was not significant, the studies within each type of memory were heterogeneous; 3) the difference in time duration between the end of saccades manipulation and the completion of memory tasks may be another reason for the inconsistent results. Since the enhancing effect of eye movements may be temporary, the benefits may not be maintained if the interval between saccades and recall was too long (Samara et al., 2011). Despite the variabilities, enhancing effect of saccades persists after taking publication bias into consideration, therefore it might be taken as a strategy to improve memory temporarily in daily lives.

As mentioned in the introduction, there are mainly two theories on the underlying mechanisms of SIRE. The interhemispheric interaction hypothesis proposed that horizontal saccades improve memory retrieval by facilitating the interhemispheric interaction of the

brain (Christman, Garvey, Propper, & Phaneuf, 2003), whereas the top-down attentional control hypothesis suggested that eye movements promote memory by improving attention control (Lyle & Edlin, 2015). Controversy between these two hypotheses can be partly elucidated by the present meta-analysis. The interhemispheric interaction hypothesis believed the retrieval of episodic memory rely on the level of interhemispheric interaction, and that any facilitation of interhemispheric interaction would improve memory retrieval. According to this theory, strongly right-handed individuals who had lower levels of interhemispheric interaction benefited more from saccades, which was supported by our results. Another important discrepancy between the two theories is whether the direction of saccades affect the effect on memory retrieval. The interhemispheric interaction hypothesis suggests that only horizontal saccades can facilitate interhemispheric interaction, which would be beneficial to memory retrieval. On the contrary, the top-down attentional control hypothesis proposes that the activation of frontoparietal network caused by saccades was the primary reason for memory improvement. According to the latter theory, saccades would improve memory retrieval no matter it is horizontal or vertical. Our results demonstrated that only horizontal saccades are beneficial to memory retrieval, which again supports the interhemispheric interaction hypothesis. Though the three EEG studies (Fleck et al., 2018; Propper, Pierce, Geisler, Christman, & Bellorado, 2007; Samara, Elzinga, Slagter, & Nieuwenhuis, 2011) did not reveal increased interhemispheric coherence after horizontal saccades manipulation, there were some limitations in these studies, such as small sample size, limited number of electrodes used to measure coherence, and lack of behavioral measures. Further neuroimaging studies with stricter experimental designs were warranted

to examine the neural mechanisms of SIRE.

Another factor worth mentioning is that the level of interhemispheric interaction is not an all-or-none phenomenon, but a continuous one. If the interhemispheric interaction hypothesis is true, then the visual angle, as well as duration of saccades should also affect the level of interhemispheric interaction, but previous studies did not take these variables into consideration. Further studies should clarify these issues.

Several limitations of the current study should be noted. First, studies included in this meta-analysis have narrow age range since most of the studies were conducted in university students, whether the effect would be presented in other age groups needs more studies. Second, the criteria of strongly right-handed and non-strongly right-handed were different from study to study; and different indexes were used for memory performance (such as autobiographical memory), these may cause the heterogeneity among the studies. Third, due to small number of studies, it is impossible to conduct moderator analyses on some factors such as the emotional valence of words or events, and age of participants.

To conclude, the present study demonstrated that horizontal saccades could improve overall memory performance. Strongly right-handed individuals are more sensitive to this effect. Vertical saccades cannot improve memory performance. These results provided support for the interhemispheric interaction hypothesis.

Funding: This study was funded by the National Science Foundation of China (31571130).

Conflict of Interest: None declared.

Ethical approval: This article does not contain any studies with human participants performed by any of the authors.

References

(Studies included in the meta-analysis are indicated by *)

*Brunye, T. T., Mahoney, C. R., Augustyn, J. S., & Taylor, H. A. (2009). Horizontal saccadic eye movements enhance the retrieval of landmark shape and location information. *Brain Cogn, 70*(3), 279-288. doi:10.1016/j.bandc.2009.03.003

Cronin Golomb, A., Gabrieli, J. D. E., & Keane, M. M. (1996). Implicit and explicit memory retrieval within and across the disconnected cerebral hemispheres. *Neuropsychology*, 10(2), 254-262. doi:10.1037/0894-4105.10.2.254

Cabeza, R., & Nyberg, L. (2000). Imaging cognition II: An empirical review of 275 PET and fMRI studies. *J Cogn Neurosci, 12*(1), 1-47. doi:10.1162/08989290051137585

Christman, S. D., & Propper, R. E. (2001). Superior episodic memory is associated with interhemispheric processing. *Neuropsychology*, 15(4), 607-616. doi:10.1037//0894-4105.15.4.607

Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience, 3*(3), 201-215. doi:10.1038/nrn755

*Christman, S. D., Garvey, K. J., Propper, R. E., & Phaneuf, K. A. (2003). Bilateral eye movements enhance the retrieval of episodic memories. *Neuropsychology, 17*(2), 221-229.

*Christman, S. D., Propper, R. E., & Dion, A. (2004). Increased interhemispheric interaction is associated with decreased false memories in a verbal converging semantic associates

paradigm. *Brain Cogn, 56*(3), 313-319. doi:10.1016/j.bandc.2004.08.005

*Christman, S. D., Propper, R. E., & Brown, T. J. (2006). Increased interhemispheric interaction is associated with earlier offset of childhood amnesia. *Neuropsychology, 20*(3), 336-345. doi:10.1037/0894-4105.20.3.336

Duval, S. , & Tweedie, R. . (2000). Trim and fill: a simple funnel-plot–based method of testing and adjusting for publication bias in meta-analysis. *Biometrics*, 56(2), 455-463.

Edlin, J. M., & Lyle, K. B. (2013). The effect of repetitive saccade execution on the attention network test: enhancing executive function with a flick of the eyes. *Brain Cogn, 81*(3), 345-351. doi:10.1016/j.bandc.2012.12.006

Fleck, J. I., Olsen, R., Tumminia, M., DePalma, F., Berroa, J., Vrabel, A., & Miller, S. (2018). Changes in brain connectivity following exposure to bilateral eye movements. *Brain Cogn, 123*, 142-153. doi:10.1016/j.bandc.2018.03.009

Hedges, L. V., & Vevea, J. L. (1998). Fixed- and random-effects models in meta-analysis. *Psychological Methods*, 3(4), 486-504. doi:10.1037/1082-989x.3.4.486

*Lyle, K. B., Logan, J. M., & Roediger, H. L., III. (2008). Eye movements enhance memory for individuals who are strongly right-handed and harm it for individuals who are not. *Psychonomic Bulletin & Review, 15*(3), 515-520. doi:10.3758/pbr.15.3.515

Lyle, K. B., & Martin, J. M. (2010). Bilateral saccades increase intrahemispheric processing but not interhemispheric interaction: Implications for saccade-induced retrieval enhancement. *Brain Cogn, 73*(2), 128-134. doi:10.1016/j.bandc.2010.04.004

*Lyle, K. B., & Jacobs, N. E. (2010). Is saccade-induced retrieval enhancement a potential means of improving eyewitness evidence? *Memory, 18*(6), 581-594.

doi:10.1080/09658211.2010.493891

Luders, E., Cherbuin, N., Thompson, P. M., Gutman, B., Anstey, K. J., Sachdev, P., & Toga, A. W. (2010). When more is less: Associations between corpus callosum size and handedness lateralization. *Neuroimage, 52*(1), 43-49. doi:10.1016/j.neuroimage.2010.04.016doi:10.1037/a0024831

*Lyle, K. B., & Orsborn, A. E. (2011). Inconsistent handedness and saccade execution benefit face memory without affecting interhemispheric interaction. *Memory, 19*(6), 613-624. doi:10.1080/09658211.2011.595418

*Lyle, K. B., Hanaver-Torrez, S. D., Hacklander, R. P., & Edlin, J. M. (2012). Consistency of handedness, regardless of direction, predicts baseline memory accuracy and potential for memory enhancement. *J Exp Psychol Learn Mem Cogn, 38*(1), 187-193. doi:10.1037/a0024831

*Lyle, K. B., & Edlin, J. M. (2015). Why does saccade execution increase episodic memory retrieval? A test of the top-down attentional control hypothesis. *Memory, 23*(2), 187-202. doi:10.1080/09658211.2013.877487

*Lyle, K. B. (2018). Effects of handedness consistency and saccade execution on eyewitness memory in cued- and free-recall procedures. *Memory, 26*(9), 1169-1180. doi:10.1080/09658211.2017.1420802

*Matzke, D., Nieuwenhuis, S., van Rijn, H., Slagter, H. A., van der Molen, M. W., & Wagenmakers, E. J. (2015). The effect of horizontal eye movements on free recall: a preregistered adversarial collaboration. *J Exp Psychol Gen, 144*(1), e1-15. doi:10.1037/xge0000038

*Nieuwenhuis, S., Elzinga, B. M., Ras, P. H., Berends, F., Duijs, P., Samara, Z., & Slagter, H. A. (2013). Bilateral saccadic eye movements and tactile stimulation, but not auditory stimulation, enhance memory retrieval. *Brain Cogn, 81*(1), 52-56. doi:10.1016/j.bandc.2012.10.003

*Parker, A., & Dagnall, N. (2007). Effects of bilateral eye movements on gist based false recognition in the DRM paradigm. *Brain Cogn, 63*(3), 221-225. doi:10.1016/j.bandc.2006.08.005

*Parker, A., Relph, S., & Dagnall, N. (2008). Effects of bilateral eye movements on the retrieval of item, associative, and contextual information. *Neuropsychology, 22*(1), 136-145. doi:10.1037/0894-4105.22.1.136

*Parker, A., Buckley, S., & Dagnall, N. (2009). Reduced misinformation effects following saccadic bilateral eye movements. *Brain Cogn, 69*(1), 89-97. doi:10.1016/j.bandc.2008.05.009

*Parker, A., & Dagnall, N. (2010). Effects of handedness and saccadic bilateral eye movements on components of autobiographical recollection. *Brain Cogn, 73*(2), 93-101. doi:10.1016/j.bandc.2010.03.005

*Parker, A., & Dagnall, N. (2012). Effects of saccadic bilateral eye movements on memory in children and adults: an exploratory study. *Brain Cogn, 78*(3), 238-247. doi:10.1016/j.bandc.2012.01.007

*Parker, A., Parkin, A., & Dagnall, N. (2013). Effects of saccadic bilateral eye movements on episodic and semantic autobiographical memory fluency. *Front Hum Neurosci, 7*, 630. doi:10.3389/fnhum.2013.00630

*Parker, A., Parkin, A., & Dagnall, N. (2017). Effects of handedness & saccadic bilateral eye movements on the specificity of past autobiographical memory & episodic future thinking. *Brain Cogn, 114*, 40-51. doi:10.1016/j.bandc.2017.03.006

*Parker, A., Powell, D., & Dagnall, N. (2018). Effects of Saccade Induced Retrieval Enhancement on conceptual and perceptual tests of explicit & implicit memory. *Brain Cogn, 121*, 1-10. doi:10.1016/j.bandc.2017.12.002

*Phaf, R. H. (2017). Eye Movements Enhance Recollection of Re-Imagined Negative Words: A Link Between EMDR And Sire? *Journal of Experimental Psychopathology, 8*(4), 364-375. doi:10.5127/jep.059916

Propper, R. E., Pierce, J., Geisler, M. W., Christman, S. D., & Bellorado, N. (2007). Effect of bilateral eye movements on frontal interhemispheric gamma EEG coherence - Implications for EMDR therapy. *Journal of Nervous and Mental Disease, 195*(9), 785-788. doi:10.1097/NMD.0b013e318142cf73

Shapiro, F. (1989). Eye movement desensitization: a new treatment for post-traumatic stress disorder. *J Behav Ther Exp Psychiatry, 20*(3), 211-217. doi:10.1016/0005-7916(89)90025-6

Shobe, E. R., Ross, N. M., & Fleck, J. I. (2009). Influence of handedness and bilateral eye movements on creativity. *Brain and Cognition, 71*(3), 204-214. doi:10.1016/j.bandc.2009.08.017

*Samara, Z., Elzinga, B. M., Slagter, H. A., & Nieuwenhuis, S. (2011). Do Horizontal Saccadic Eye Movements Increase Interhemispheric Coherence? Investigation of a Hypothesized Neural Mechanism Underlying EMDR. *Front Psychiatry, 2*, 4.

doi:10.3389/fpsyt.2011.00004

Tulving, E., Kapur, S., Craik, F. I. M., Moscovitch, M., & Houle, S. (1994). Hemispheric encoding/retrieval asymmetry in episodic memory: Positron emission tomography findings. *Proceedings of the National Academy of Sciences of the United States of America*, 91(6), 2016-2020. doi:10.1073/pnas.91.6.2016

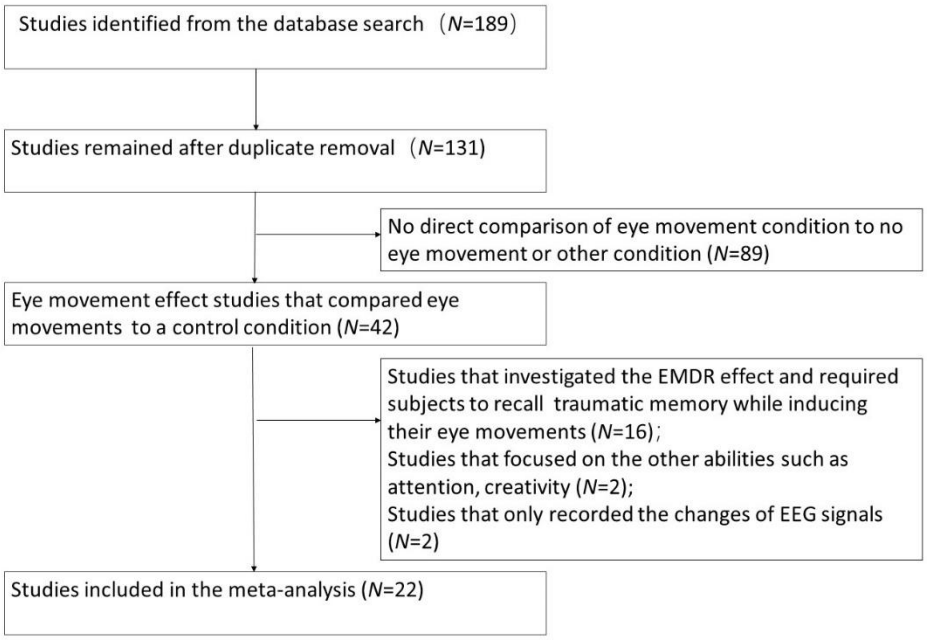
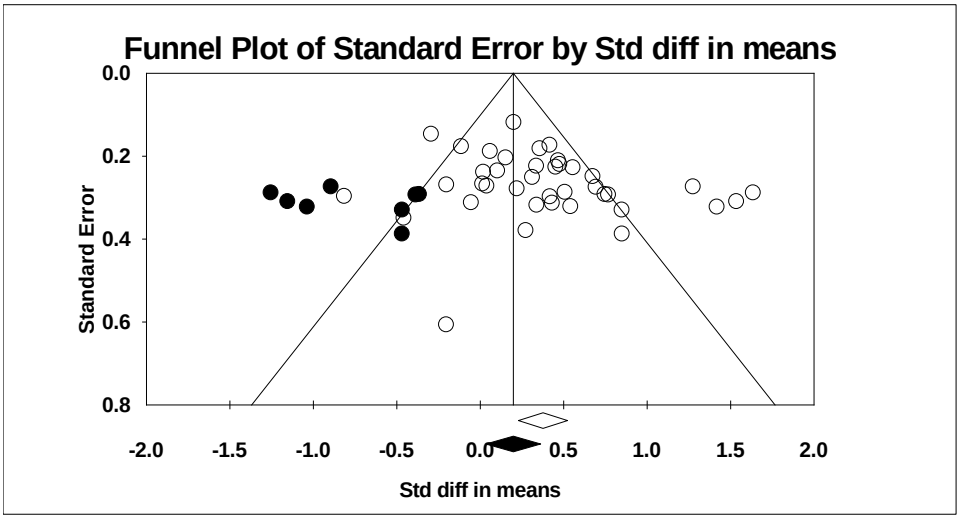


Fig.1 Flow chart of selection and inclusion process following the PRISMA statement

(a)



(b)

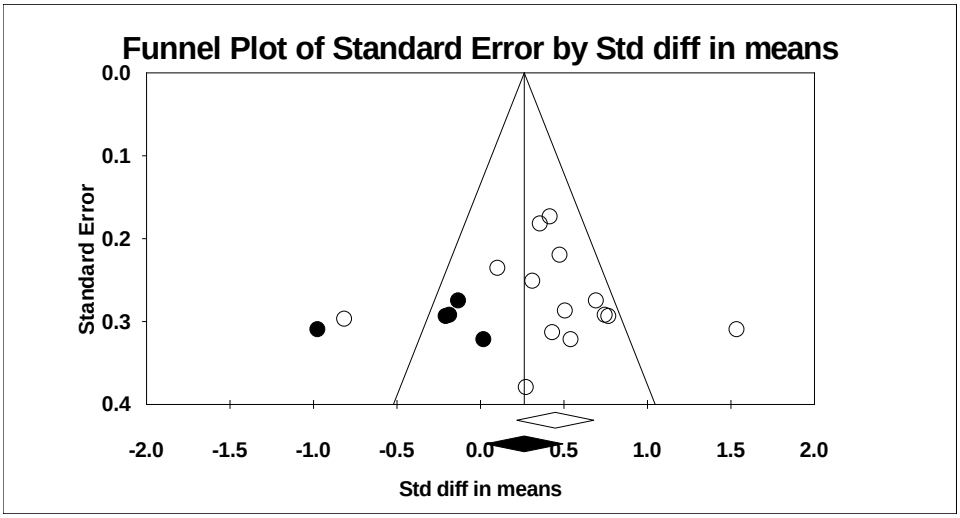


Fig.2 Funnel plots for the trim and fill procedure. (a) Results for all comparisons including strongly right-handed, non-strongly right-handed and handedness unknown groups; (b) Results for strongly right-handed group only. White dots stand for all studies included in the meta-analysis; black dots indicate studies that adjusted for the publication bias.

Table 1 Summary of studies included in the meta-analysis

Study	*N*			Type of memory	Outcome measures	Material	Eye movements manipulation
	Horizontal saccades group	Vertical saccades group	No eye movements group				
Christman et al., 2003 (exp1)	28	28	28	Episodic memory	d', β	Word list	Horizontal saccades, vertical saccades, horizontal smooth eye movements, vertical smooth eye movements, no eye movements
Christman et al., 2003 (exp2)	20	-	20	Autobiographical memory	d', β	-	Horizontal saccades, no eye movements
Christman et al., 2004 (exp2)	20	-	20	False memory	Critical lures falsely recalled, other falsely recalled, number of correct recalls	Word list	Horizontal saccades, no eye movements
Christman et al., 2006	42	-	38	Autobiographical memory	Age of childhood memory	-	Horizontal saccades, no eye movements
Parker & Dagnall, 2007	34	34	34	False memory	Hit rate, false alarm, d', β	Word list	Horizontal saccades, vertical saccades, no eye movements
Parker et al., 2008 (exp1)	32	32	32	Episodic memory	Hit rate, false alarm, d', β, remember–know responses	Word list	Horizontal saccades, vertical saccades, no eye movements
Parker et al., 2008 (exp2)	32	32	32	Episodic memory	Correct response proportion	Word list	Horizontal saccades, vertical saccades, no eye movements
Lyle et al., 2008 (exp1)	69	-	70	Episodic memory	Number of correct recalls, number of false recalls	Word list	Horizontal saccades, no eye movements

Lyle et al., 2008 (exp2)	38	39	38	Episodic memory	Hit rate, false alarm , d'	Word list	Horizontal saccades, vertical saccades, no eye movements, free viewing
Parker et al., 2009	24	24	24	False memory	Hit rate, false alarm rate, d', β, remember–know responses	Picture and narrative	Horizontal saccades, vertical saccades, no eye movements
Bruyne et al., 2009 (exp1)[a]	36	36	36	Episodic memory	Hit rate, false alarm rate, d', response time	Picture	Horizontal saccades, vertical saccades, no eye movements
Brunye et al., 2009(exp2)	36	36	36	Episodic memory	Hit rate, false alarm rate, d', response time	Picture	Horizontal saccades, vertical saccades, no eye movements
Parker & Dagnall, 2010	40	-	40	Autobiographical memory	Reliving, emotion, subject/observer etc	Cue words	Horizontal saccades, no eye movements
Lyle & Jacobs, 2010 (exp1)	64	-	64	False memory	Hit rate, false alarm rate, d', confidence in memories	Slideshows depicting crimes	Horizontal saccades, no eye movements
Lyle & Jacobs, 2010 (exp2)	52	-	52	False memory	Hit rate, false alarm rate, d', confidence in memories	Slideshows depicting crimes	Horizontal saccades, no eye movements
Lyle & Orsborn, 2011[a]	32	-	32	Not clear to be classified	Correct response proportion	Famous face	Horizontal saccades, no eye movements
Samara et al., 2011[a]	14	-	14	Episodic memory	Number of recalls	Word list	Horizontal saccades, no eye movements
Lyle et al., 2012[a]	120	-	120	Episodic memory	Hit rate, false alarm rate, d', response time	Word pairs	Horizontal saccades, no eye movements
Parker & Dagnall, 2012	46	46	46	False memory	Hit rate, false alarm rate, d', β	Word list	Horizontal saccades, vertical saccades, no eye movements
Parker et al., 2013	23	23	23	Autobiographical memory	Number of recalls	-	Horizontal saccades, vertical saccades, no eye movements

Nieuwenhuis et al., 2013	25	-	25	Episodic memory	Number of recalls	Word list	Horizontal saccades, no eye movements
Matzke et al.,2014	25	24	24	Episodic memory	Number of correct recalls	Word list	Horizontal saccades, vertical saccades, no eye movements
Lyle & Edlin, 2015 (exp1)	72	-	76	Episodic memory	Correct response proportion	Word list	Horizontal saccades, no eye movements
Lyle & Edlin, 2015 (exp2)	-	18	22	Episodic memory	A[b]	Drawing and name	Vertical saccades, no eye movements
Phaf, 2017	20	-	20	Episodic memory	Number of recalls	Word list	Horizontal saccades, no eye movements
Parker et al., 2017	26	26	28	Autobiographical memory	Specific, extended, categorical	Sentence	Horizontal saccades, vertical saccades, no eye movements
Parke et al., 2018	25	-	25	Episodic memory	Correct response proportion	Word list	Horizontal saccades, no eye movements
Lyle, 2018 (exp1)	55		56	Episodic memory	Accuracy, confidence in memories	Slideshows depicting crimes	Horizontal saccades, no eye movements
Lyle, 2018 (exp2)	87		81	Episodic memory	Number of recalls, accuracy	Slideshows depicting crimes	Horizontal saccades, no eye movements

Note: [a] Studies that comparing saccades to a control condition with a within-group design;

[b] A nonparametric index of sensitivity

Table 2 Saccade-induced retrieval enhancement for all studies and different types of memory

Study	*K*	*d*	95% *CI*	*Z*	*Q*
All studies	28	0.45	0.29-0.62	5.40***	113.96***
Episodic memory	16	0.37	0.14-0.59	3.22**	72.81***
Autobiographical memory	5	0.68	0.31-1.06	3.57***	9.81*
False memory	6	0.57	0.23-0.92	3.28**	16.43**
Not clear to be classified	1	0.12	-0.13-0.37	0.92	-

Note: *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$

Table 3 Saccade-induced retrieval enhancement for different handedness groups

Study	*K*	*d*	95% *CI*	*Z*	*Q*
All comparisons	39	0.38	0.23-0.52	5.4***	133.58***
Strongly right-handed	14	0.45	0.22-0.68	3.81***	36.35**
Non-strongly right-handed	11	-0.06	-0.20-0.09	-0.77	10.12
Handedness unknown	14	0.60	0.36-0.85	4.76***	52.41***

Note: **: $p < 0.01$; ***: $p < 0.001$

Table 4 Publication Bias and adjusted effect sizes

Study	*d*	Egger's intercept	*t*	*N*	adjusted *d*	95% *CI*
All comparisons	0.38	2.04	2.07*	8	0.20	0.03-0.36
Strongly right-handed	0.45	0.94	0.45	5	0.26	0.03-0.50
Non-strongly right-handed	-0.06	0.82	0.86	1	-0.08	-0.22-0.06
Handedness unknown	0.60	4.20	3.11*	5	0.31	0.03-0.60

Note: *: $p < 0.05$

N: number of missing studies that need to imputed according to the Trim and Fill adjustment